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16. Abstract

Data from the U.S. Fatal Accident Reporting System (1980 - 1993) were examined to test the hypothesis that age-related changes of vision are associated with increased involvement in fatal accidents under low illumination. A quasi-experimental analysis of 626,893 cases investigated the effects of light condition, driver age, and driver gender for two categories of fatal accidents, *Pedestrian/pedalcycle* vs. all *Others* combined. The investigation focused on monthly variations in the distribution of accidents occurring under three light conditions: (1) *Twilight Zones*, in which natural illumination varied on a monthly basis with the annual solar cycle; (2) *Daylight Control*; and (3) *Nighttime Control*. Within each light condition, cases were subdivided by drivers' age and gender. The results showed a substantial increase in the proportion of fatal *pedestrian/pedalcycle* cases in the *Twilight Zones* during the winter when natural illumination is dim, as compared with the summer when it is bright. This monthly variation was attributed to changes in visibility, rather than other seasonal variables, because there were no parallel variations for the *Daylight* condition when visibility is uniform throughout the year. The elevated incidence of fatal *pedestrian/pedalcycle* accidents in the dim months of the *Twilight Zones* grew progressively with increasing age, approximately doubling in magnitude across the adult life span to the age of retirement, after which the overrepresentation of cases in dim months receded toward that of middle-aged drivers. A similar, but smaller, age-related increase in the relative incidence of *Other* (non-ped.) cases during the dim months of the *Twilight Zones* was also identified. Results from the *Daylight* condition showed no relative increase in accident involvement during the winter months for either accident class, but, on the contrary, revealed a reduction of winter accidents with increasing age. These control data discount the potential contribution of seasonal variables other than illumination to the elevated incidence of fatal accidents during the winter (dim) months in the *Twilight Zones*. The present findings provide new evidence that age-related changes in basic visual processes, which cause gradual deterioration of night vision, contribute to increasing involvement in fatal accidents, particularly with pedestrians and pedalcyclists, in low illumination.

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CONTENTS

INTRODUCTION

Legend has it that driving is 90% visual. Although the quantitative status of this assertion is dubious and the specific visual functions are as yet unspecified (Sivak, 1995), there is wide agreement that impaired vision represents an unsafe condition, and all known jurisdictions require a vision test to obtain a motor vehicle operator's license. Yet empirical quantification of the extent to which visual impairment contributes to traffic mishaps is scarce. The purpose of the present investigation was to quantify the contributions of the common causes of visual impairment, namely, reduced illumination and aging, to fatal road accidents under conditions of low illumination.

A recent analysis of data from the Fatal Accident Reporting System (NHTSA, annual) showed that visibility is a key factor in fatal mishaps involving pedestrians and pedalcyclists (Owens & Sivak, 1993). That study took a novel approach that aimed to isolate, through a quasi-experimental design, conditions in which visibility varied systematically, while other factors relevant to traffic safety would be relatively constant. The key independent variable was the variation of natural illumination associated with the Annual Twilight Cycle (Figure 1). The times of sunrise and sunset vary continuously between the summer and winter solstices over a time range of approximately 3 hours, which, in the continental U.S., ranges from about 4:00 to 7:00 in the morning and from about 17:00 to 20:00 (Standard Time) in the evening. These time periods, called *Twilight Zones*, were used as a natural experimental condition for evaluating the role of illumination, and thus visibility, in fatal traffic accidents.

Owens and Sivak's (1993) first quasi-experimental analysis focused on the light conditions that prevailed for 104,235 fatal accidents, which occurred during the Twilight Zone test periods between the years of 1980 and 1990. Because over the course of a year the Twilight Zones comprise roughly equal periods of daylight and dim illumination (46.8% vs. 53.2%, respectively), it was hypothesized that, if natural illumination were *not* a causal factor, then fatal accidents would be distributed in similar proportions across light and dim conditions. Contrary to this null hypothesis, the data showed that 65.3% of the fatal events occurred under dim conditions. This overrepresentation was not related to time of day (morning vs. evening), day of week (weekends vs. weekdays), or drivers' consumption of alcohol.

The overrepresentation of fatal crashes in low illumination increased when analyses focused on conditions defined more narrowly as involving greater visual difficulty. In degraded atmospheric conditions, for example, 78.8% of the fatal accidents recorded in the Twilight Zones occurred in dim illumination. Similarly, when crashes were classified according to the object of collision, the representation of pedestrian and pedalcycle accidents in dim illumination was found to be much higher (78.7%) than that for all other fatal accidents (61.2%). Combining these variables yielded still greater variations in the distribution of fatal accidents. When degraded atmosphere and collisions with pedestrians and pedalcycles were excluded, the proportion of fatal collisions in dim illumination fell to 58.9%, just 5.7% above the chance prediction. In contrast, when analyses focused on degraded atmospheric conditions combined with the low-visibility characteristics of pedestrian/pedalcyclist accidents, the proportion of accidents occurring in dim illumination reached 92.3%, nearly 40% above chance. This pattern of findings was unchanged when analyses excluded collisions that involved drinking drivers.

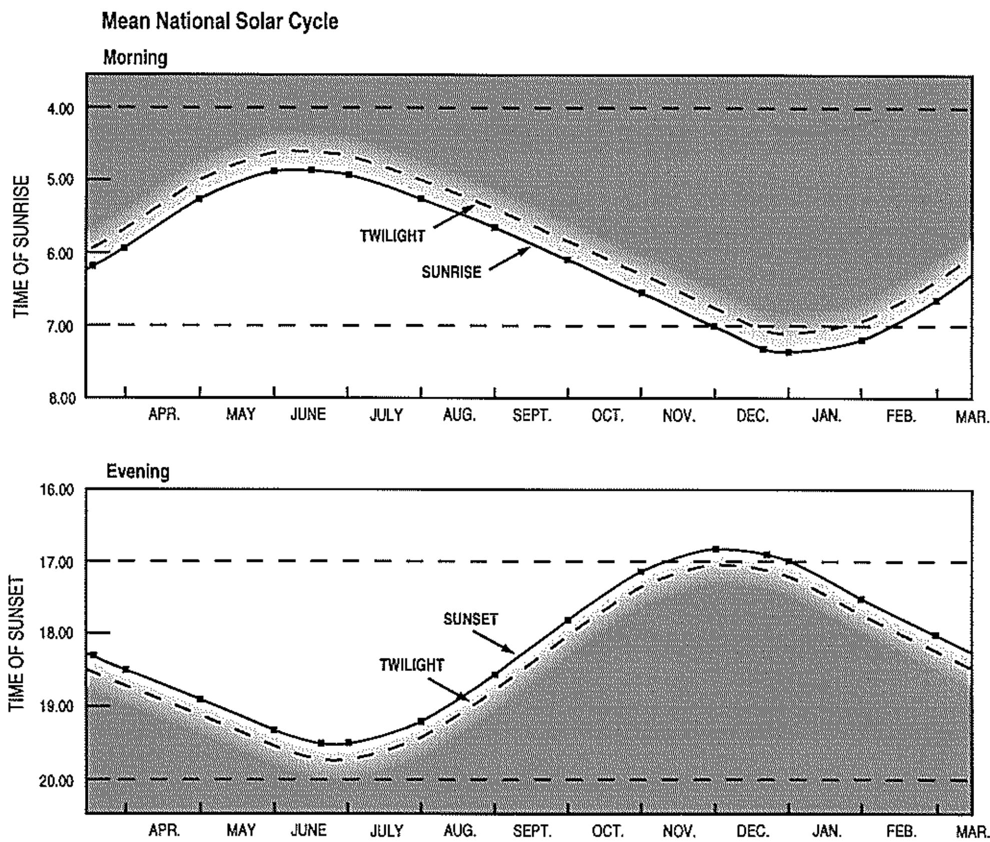

Figure 1. The Mean National Solar and Twilight Cycles based on the ephemeris at mid-latitude of the 48 contiguous United States. Shaded areas represent darkness and unshaded, daylight. Dashed curves represent the mid-point of Civil Twilight; dashed horizontal lines represent the boundaries of the *Twilight Zones* test condition.

Owens & Sivak's (1993) second quasi-experiment examined monthly variations in the distribution of fatal accidents, which could be related either to changes in ambient illumination or to some other seasonal variable that is unrelated to visibility. Again, accidents during the twilight-zones test periods were of special interest because of natural variations in ambient illumination. Results from the first quasi-experiment suggested that accident rates during the twilight-zone periods would increase in the darker months. It is possible, however, that such increased accident rates are due to seasonal factors, such as weather or variable travel patterns, that are unrelated to visibility. To evaluate this possibility, fatal accidents during two additional control periods were examined: a Daylight Control period including two three-hour time blocks that follow the morning and precede the evening twilight zones, and a Nighttime Control including the two three-hour blocks that follow evening and precede morning twilight zones (Table 1).

Table 1. Definition of test periods of Twilight, Daylight, and Nighttime for Standard and Daylight Savings Time.

Data Set	**Clock-Times Included**	
	Standard Time	**Daylight Savings Time**
Twilight Zones	0400 - 0659 hr. 1700 - 1959 hr.	0500 - 0759 hr. 1800 - 2059 hr.
Daylight Control Period	0700 - 0959 hr. 1400 - 1659 hr.	0800 - 1059 hr. 1500 - 1759 hr.
Nighttime Control Period	2000 - 2259 hr. 0100 - 0359 hr.	2100 - 2359 hr. 0200 - 0459 hr.

The key question was whether the distribution of accidents falling into these three test periods would vary across months of the year. Effects due to light condition (visibility) should appear only in data from the twilight-zone test periods, because that is when ambient illumination varies from month to month, as illustrated in Figure 1. Effects due to seasonal variables *other than* light condition were expected to affect the frequency of accidents in one or both of the Control Periods, as well as in the *Twilight Zones*. For example, changes in the exposure of children, as they disband for vacation in the late spring and return to school in the fall, would be expected to show up in the *Daytime Control* Period. Monthly data for pedestrian/pedalcycle accidents as compared with all other fatal accidents were examined separately because the earlier analysis indicated that light condition has differential effects for these two classes of accidents.

As seen in Figure 2, when pedestrian/pedalcycle incidents were excluded, the results showed no change in accident patterns associated with variations of ambient illumination. The monthly percentage of fatal accidents in the Twilight Zones was nearly constant year round at approximately 22.5%. A different pattern emerged from analyses of fatal pedestrian and pedalcycle accidents. Here the accident rate in the Twilight Zones varied widely in exactly the pattern predicted by variations of natural illumination. Meanwhile, there was no evidence in data from either Control Period to suggest that other seasonal variables might contribute to elevated fatal pedestrian/pedalcycle accident rates in the Twilight Zones during the darker months. These findings indicate that visibility is an important contributor to fatal pedestrian and pedalcycle accidents, and they suggest that other classes of fatal accidents are not so sensitive to variations in natural illumination.

The present study extends the investigation of Owens and Sivak (1993) to address the possible contribution of age-related changes of vision to fatal traffic accidents. Many visual functions are adversely affected by the normal aging process. Perhaps most notable are *presbyopia*, which reflects diminished ocular accommodation, and impaired night vision, which arises from miosis (contraction) of the pupil. Both of these oculomotor changes occur gradually and progressively throughout the adult life span of all individuals. Though less clearly understood, deterioration of visual neural processing is apparently also a common occurrence in many healthy individuals, particularly beyond the fifth or sixth decade. Moreover, a variety of visual pathologies (e.g., cataracts, glaucoma, macular degeneration) and associated visual impairments are increasingly common with advancing age.

Problems with night driving are among the most commonly reported visual complaints associated with aging (Kosnik, Sekuler, & Kline, 1990; Schieber, 1994; Waller, 1991). Many older individuals voluntarily restrict or cease driving in low illumination. Such difficulties with night driving are of growing concern as the population ages, for they point toward potential problems of safety and mobility that might be addressed through improved transportation systems. At a theoretical level, voluntary avoidance of night driving is interesting because it suggests that older drivers are aware of visual limitations that seem to be of little concern to younger drivers (Leibowitz & Owens, 1977; Leibowitz & Owens, 1986; Leibowitz, Owens, & Post, 1982). A fuller understanding of why the older individuals avoid nighttime driving could help to explain why young drivers are overconfident and routinely overdrive their headlights at night. It is possible, for example, that visual guidance systems, which remain highly efficient in low light for young drivers, lose efficiency in low light for older drivers (Owens & Tyrrell, 1993; Warren, Blackwell, & Morris, 1989).

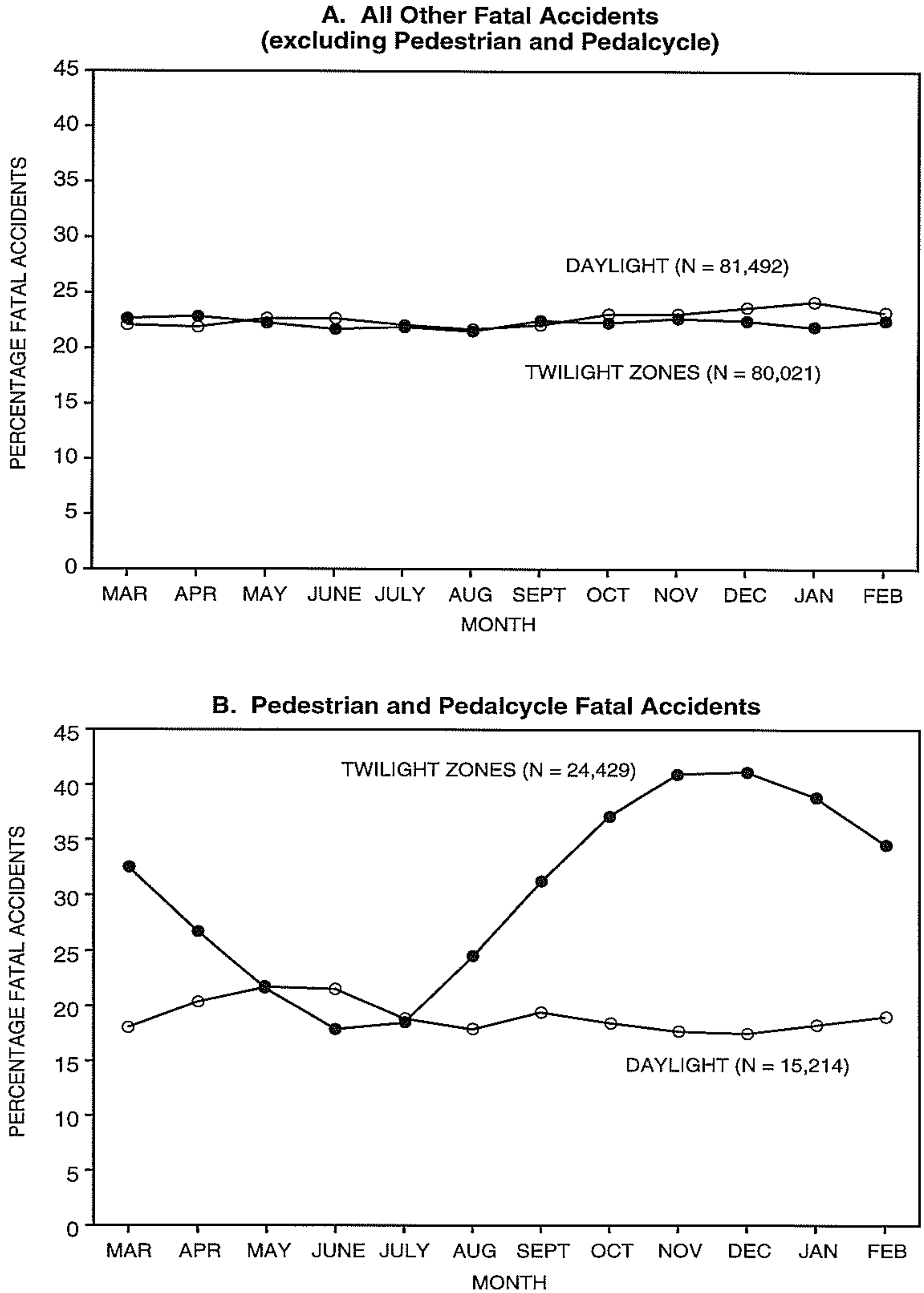

Figure 2. Percentage of total fatal accidents for each month from 1980 through 1990 in *Twilight Zones and Daylight Control* test conditions. (After Owens & Sivak, 1993)

METHOD

The present study examined fatal accidents of female and male drivers of seven age groups: <25, 25-34, 35-44, 45-54, 55-64, 65-74, and 75-97 years. Unlike the previous study by Owens and Sivak, data in the present study were coded by *driver* rather than by fatal *accident*. Consequently, the number of cases is larger for a given time period just because the number of drivers exceeded the number of fatal events that occurred. Data representing the three light conditions (the Twilight Zones, Daylight, and Nighttime Control Periods) were extracted from the FARS records for the years 1980 through 1993, three years longer than the previous study. Thus, the present data set included all drivers who were involved in a fatal accident under any of the three experimental light conditions. These data were compiled by month over 14 years, for 47 contiguous United States.[1] Clock times for subsets of data representing the three light conditions were adjusted for Daylight Savings Time relative to the solar/twilight cycle following the procedure introduced by Owens & Sivak (1993) as summarized in Table 1. Details can be found in the previous report.

[1] Data from the state of Arizona were excluded because that state does not alternate between Standard and Daylight Savings Time and, therefore, could note be coded accurately by the routine used to build the data set for the other 47 states.

RESULTS

According to FARS records, 856,522 drivers were involved in fatal accidents in 47 states during the 14 years studied. Of this total, records for 842,448 (98.4%) had been coded for both gender of the driver and class of accident (pedestrian/pedalcycle vs. other). 626,893 (74.4%) of these cases occurred during the (combined) three test periods of this experiment and were also coded for age of the driver. This comprised the primary data set for the present study. Divided by gender, 135,691 (21.6%) of the primary data set were female drivers, and 491,202 (78.4%) were male drivers. Table 2 summarizes the data for the three test periods (light conditions), subdivided into pedestrian/pedalcycle and all other fatal accidents, and divided by gender.

Each of the three test conditions included a total daily interval of 6 hours. Thus, if fatal accidents were distributed equally across 24 hours, 25% of the cases would fall within each test condition. This can be considered the null hypothesis. It is evident in Table 2 that data for several conditions exceed this null (chance) prediction: Fatal pedestrian/pedalcycle accidents were most prevalent in the *Twilight Zones* Condition (32.9% for females and 30.9% for males); they also exceeded the null prediction for male drivers in the *Nighttime Control* (29.2%). The proportion of drivers involved in *Other* (non-ped.) fatal accidents exceeded the null prediction during the *Daylight Control* for females (31.7%) and during the *Nighttime Control* for males (26.9%). These results are generally similar to those reported by Owens and Sivak (1993, Experiment 2, Table 3), with one notable difference: The relatively low accident rate for female drivers in the *Nighttime Control* condition (19.3%) was not evident in the previous study because those data were not coded by driver and, therefore, could not be subdivided by gender.

The dashed functions in Figure 3A represent the total number of drivers, divided by age and gender, involved in fatal traffic accidents during the 14-year test period. The parallel solid lines represent the subset of cases that occurred during the combined test conditions of the present study. Figure 3B illustrates the percentage of total cases for each gender and age category that were included in the present study. One should recall that the selected test conditions included 18 hours or 75% of the time per day. Thus, Figure 3 shows that these test conditions captured approximately 75% of total fatal accident cases through age 64. The proportion of cases included in the present test conditions declined for the two groups beyond age 64, reaching 64.2% for males and 60% for females in the oldest group. It is possible that this decline reflects older drivers' voluntary avoidance of driving during the low illumination test conditions.

Table 2. Distribution of Drivers involved in Fatal Accidents Subdivided by Gender, Test Period, and Accident Class.

	ACCIDENT CLASSES		
Data Set	**Pedestrian/Pedal.**	**All Other (Non-Ped.)**	**Combined**
Females:			
Twilight Zones (col %)	9,151 (32.9%)	33,761 (21.7%)	42,912 (23.4%)
Daylight Control (col %)	6,625 (23.8%)	49,331 (31.7%)	55,956 (30.5%)
Nighttime Control (col %)	6,889 (24.8%)	29,934 (19.3%)	36,823 (20.1%)
24-Hour Total (row %)	27,828 (15.2%)	155,407 (84.8%)	183,235 (100%, Females)
Males:			
Twilight Zones (col %)	28,885 (30.9%)	130,338 (23.0%)	159,223 (24.2%)
Daylight Control (col %)	17,365 (18.6%)	134,864 (23.8%)	152,229 (23.1%)
Nighttime Control (col %)	27,358 (29.2%)	152,392 (26.9%)	179,750 (27.3%)
24-Hour Total (row %)	93,503 (14.2%)	565,710 (85.8%)	659,213 (100%, Males)
Total: (row %)	121,331 (14.4%)	721,117 (85.6%)	842,448 (100%)

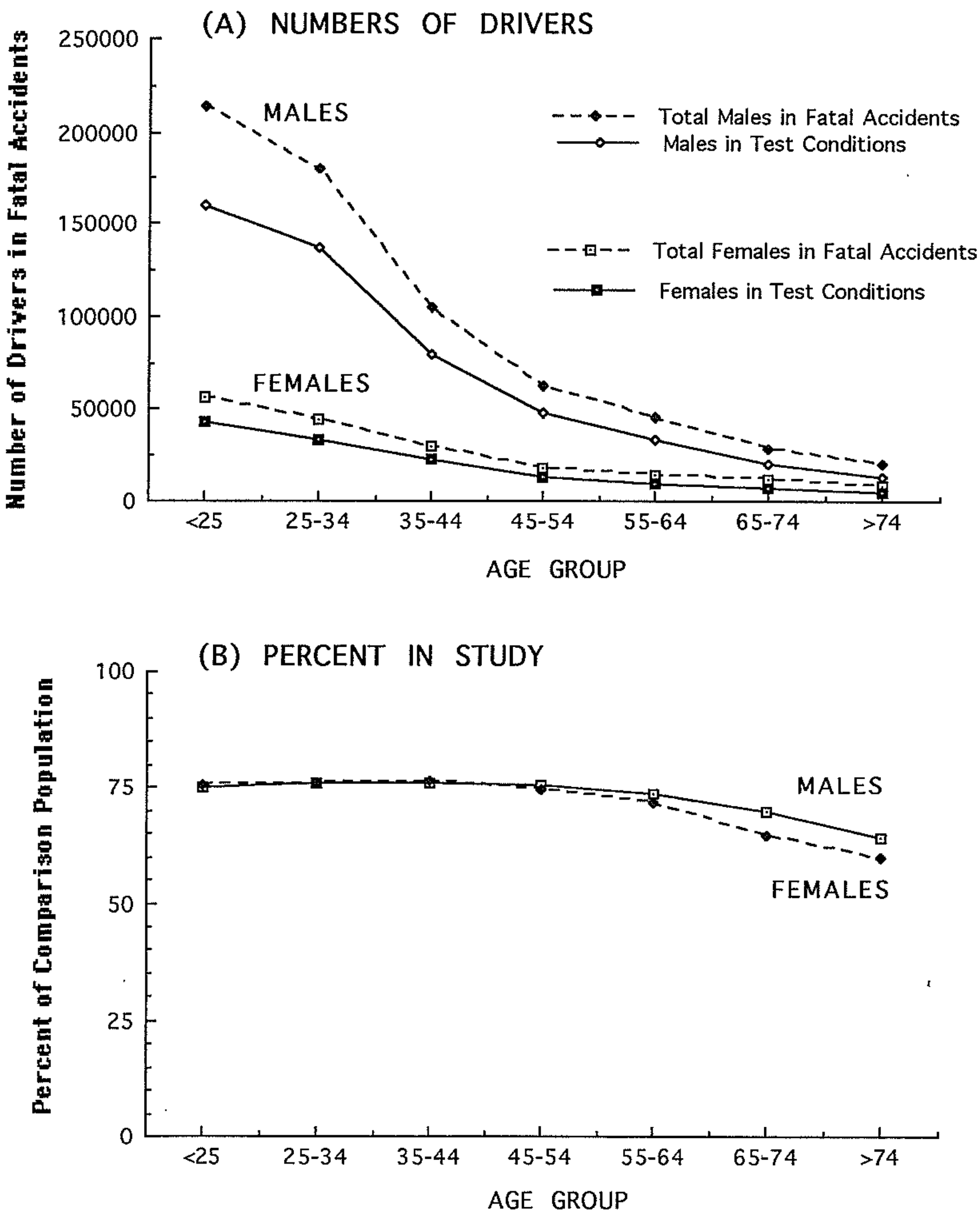

Figure 3. (A) The total numbers of male and female drivers who were involved in fatal accidents in the U.S. from 1980 - 1993, and (B) the percent of drivers included in present test conditions for each age group.

The monthly accident rates for all cases that occurred during the present test conditions, subdivided by gender and accident class (*Pedestrian/Pedalcycle* vs. *Other*), are presented in Figure 4. Values for each month represent the percentage of fatal cases in each of the three test periods, using the total number of fatal cases for that month, totaled across the 14 years of records (1980-93), as the denominator. Similar to earlier findings (Figure 2), there are wide variations for both genders in the portion of fatal *Pedestrian/Pedalcycle* cases in the *Twilight Zones* condition, while the functions for *Other* fatal accidents are nearly flat, showing little monthly variation. This replicates the previous evidence that variation in natural illumination is a contributing factor in fatal pedestrian/pedalcycle accidents, while it has relatively little impact on combined categories of other fatal accidents (Owens & Sivak, 1993). The present data extend previous findings by showing that the variations in fatal pedestrian/pedalcycle accidents are highly similar for female and male drivers. A gender difference for both accident classifications is evident, however, in data for *Daylight* and *Nighttime Control* periods, where the proportion of fatal cases for female drivers tended to be higher in the *Daylight* and that for males tended to be higher in the *Nighttime Control.*

In order to evaluate age-related factors, the data for males and females involved in both classes of fatal accidents were subdivided into seven age categories by decade. Figures 5 and 6 present the records for four of the age groups, including <25, 35-44, 55-64, and > 75 years. Two points are of particular interest here. First, all functions in Figure 6, which represent data for *Other* (non-ped.) accident cases, are generally flat, showing little variation for any of the test conditions across months of the year. In contrast, the data in Figure 5, which represent *Pedestrian/Pedalcycle* cases, show wide variations, particularly in the *Twilight Zones*, where fatality rates are consistently higher in darker months (i.e., Nov, Dec, & Jan) than in brighter months (i.e., May, June, & July). Some monthly variations are also evident in data from the *Daylight* and *Nighttime Control* conditions, but these changes are inconsistent and provide no evidence of a seasonal variable other than light condition that could account for the systematic variations in data from the Twilight Zones. This pattern of results was found for both genders at all ages, although the pattern is somewhat irregular in the oldest age groups where the number of cases is relatively small. The second point of interest concerns the interaction of gender and test period, which appears to be unrelated to month. This interaction is seen most readily by comparing *Daylight* and *Nighttime Control* data. Younger male drivers, in particular, appear to be involved in a disproportionate number of nighttime fatalities, while older males, and females of all ages, show nighttime fatality rates that are similar to or lower than daytime rates.

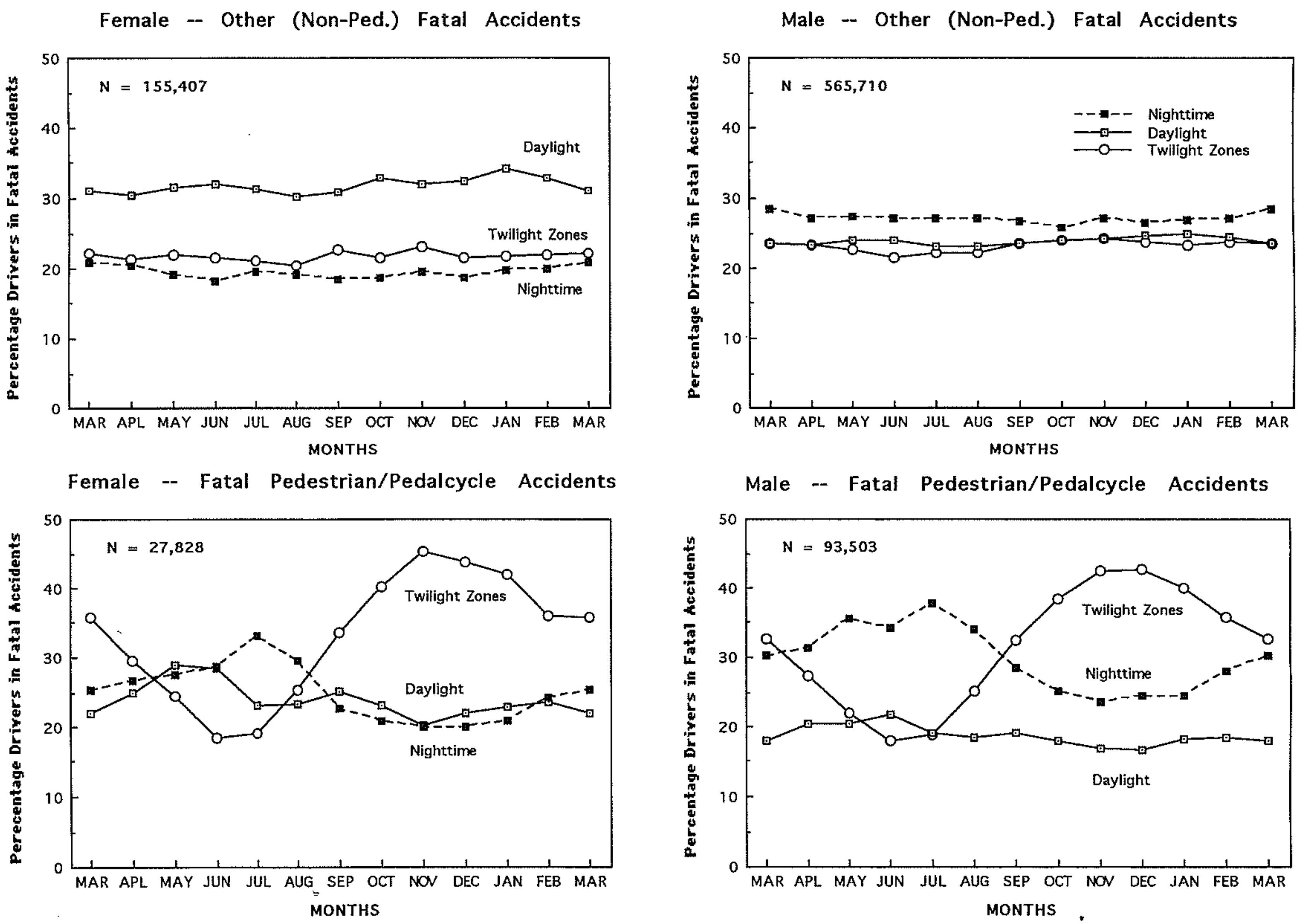

Figure 4. Percentage of fatal accidents of two classes (*Other* vs. *Pedestrian/pedalcycle*) in three test conditions for female and male drivers.

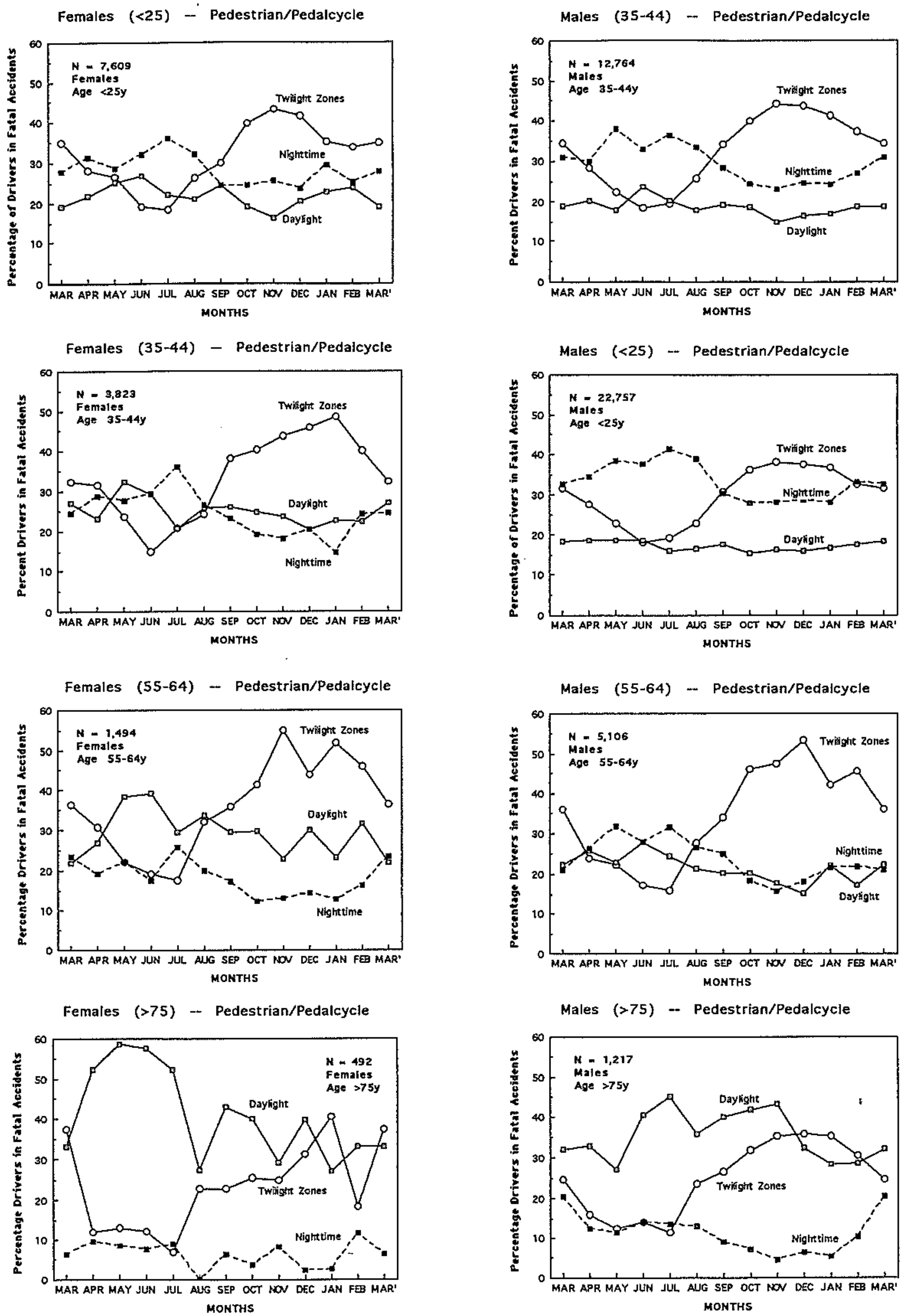

Figure 5. Percentage of fatal *Pedestrian/pedalcycle* accidents in three test conditions for female and male drivers of four age groups .

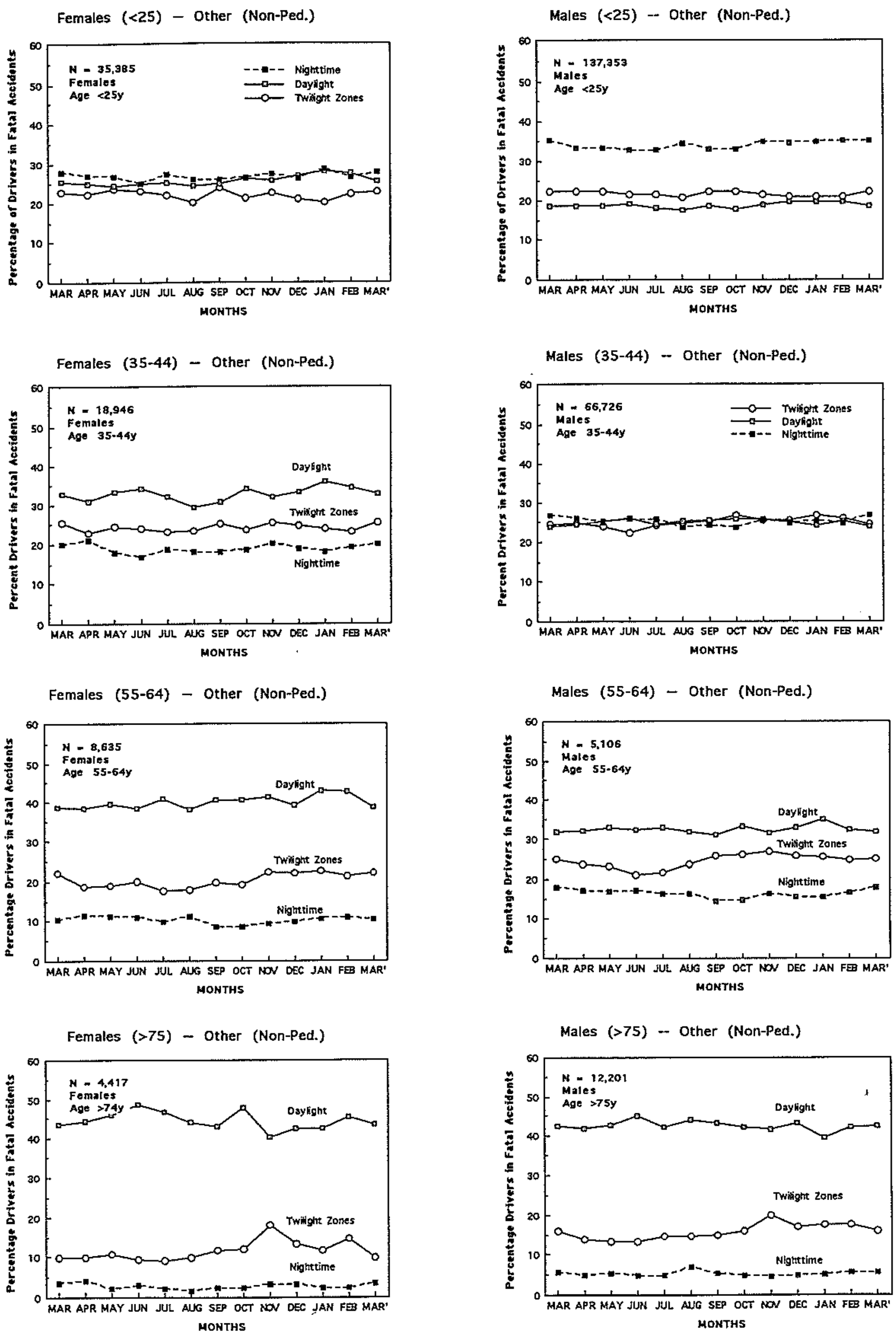

Figure 6. Percentage of *Other* (non-ped.) fatal accidents in three test conditions for female and male drivers of four age groups.

The interaction between gender, age, and light condition is summarized in a simpler format in Figure 7. Here the data have been collapsed across months and are presented as the percentage of total fatal cases (all 24 hours) that occurred in each of the three test conditions as a function of age. Data for females are given in the upper panel and those for males in the lower panel. For the youngest females, there was a slightly higher representation of fatal cases in the *Nighttime Control* (27%) as compared with the *Daylight Control* (25%) and *Twilight Zones* (23.6%). In subsequent age groups, there was a progressive decline in the proportion of cases in *Nighttime* and *Twilight Zones* (to 3% and 12.6%, respectively) and a concomitant increase in the proportion in *Daylight* (to 44.4%). In contrast, the records for males show a substantially higher representation of cases in the *Nighttime* for the two younger age groups (33.8% for the <25 and 30.5% for the 25-34 yrs. groups), while the records for age groups of 35-44 yrs. and older resemble those for females. Similar to the oldest females, records for the oldest males show the greatest proportion of cases in the *Daytime* (42.1%) and substantially lower proportions in the *Twilight Zones* (16.5%) and *Nighttime* (5.6%). It is worth noting that, unlike the records for *Nighttime* and *Daylight Controls*, data from the *Twilight Zones* are generally similar for male and female drivers.

To evaluate the effects of age-related changes in vision, further analyses focused on fatal *Pedestrian/Pedalcycle* accidents. Figure 8 presents the percentage of cases for drivers of each age group, subdivided by gender, that were involved in a fatal pedestrian or pedalcycle collision. For drivers beyond the age of 35 yrs., there was a general decline in the proportion of fatal cases involving a pedestrian or pedalcyclist. In the two youngest age groups, a somewhat higher proportion of cases with female than with male drivers also involved a pedestrian or pedalcycle. The proportions of pedestrian/pedalcycle cases for males and females are generally similar for other age groups, with the exception of the 65-74 yrs. group in which a higher proportion of cases for male drivers involved pedestrians or pedalcycles.

As discussed earlier, the role of reduced visibility as a contributor to fatal accidents can be seen as covariations in the occurrence of fatal events with changes in natural illumination during the *Twilight Zones* test condition. Of particular interest are the differences between the months in which the *Twilight Zones* are dim and daylight. As seen in Figures 2 and 4, a substantially higher proportion of the monthly fatal pedestrian and pedalcycle accidents occur during months in which the *Twilight Zones* are dim (winter) as compared with those in which the *Twilight Zones* are light (summer). Because such monthly variations are not found in the *Daylight* and *Nighttime Control* conditions, and they are not evident in any test condition for *Other* fatal accidents, they can be attributed to

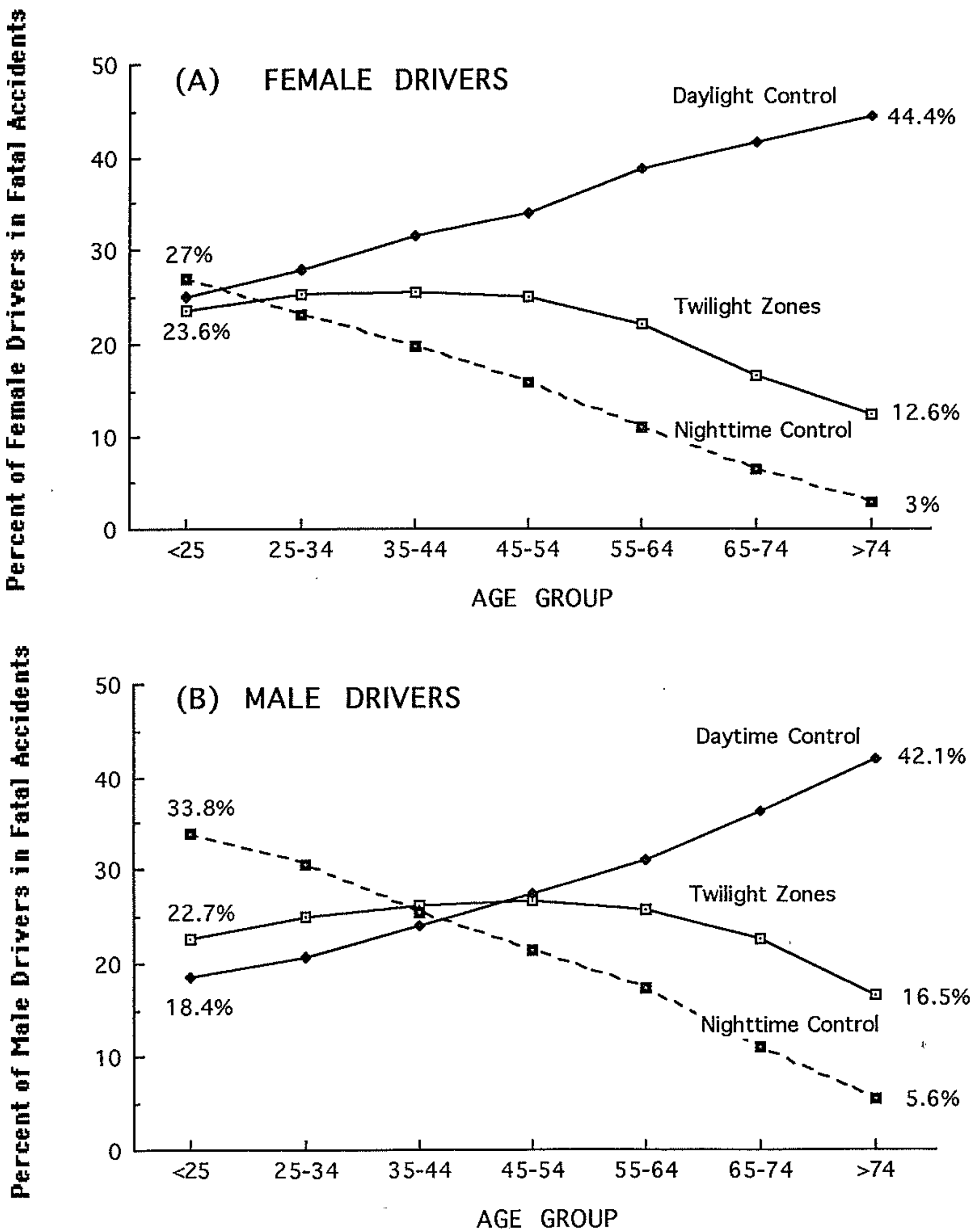

Figure 7. Percent of female (A) and male (B) drivers in fatal accidents during each test period as a function of age.

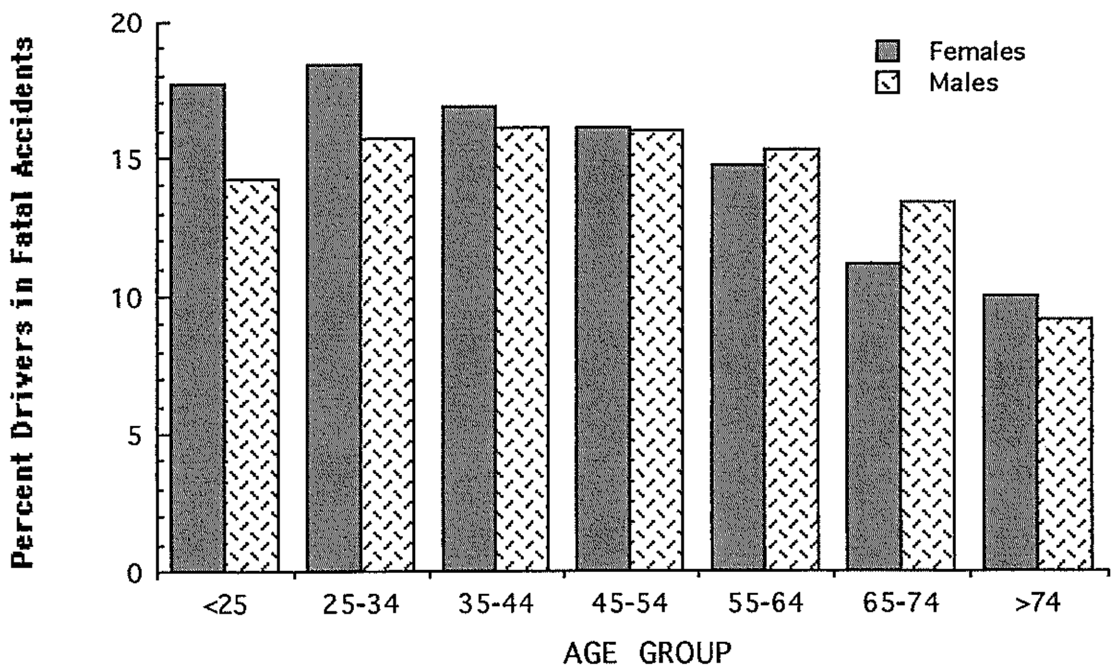

Figure 8. Percent of female and male drivers involved in fatal *Pedestrian/pedalcycle* accidents as a function of age.

the detrimental effects of reduced ambient illumination on drivers' ability to see pedestrians and pedalcyclists in time to avoid mishap (Owens & Sivak, 1993). Following this line of reasoning, we predicted that because drivers of advancing age experience progressive impairment of night vision, they will also exhibit progressively greater differences in their involvement in fatal pedestrian and pedalcycle accidents between the light and dim phases of the *Twilight Zones*. That is, if vision is a key factor, then older drivers should show relatively greater problems in vision-related accidents in the darker (winter) phase as compared with the lighter (summer) phase of the Twilight Zones. In order to test this hypothesis, we compared the proportions of fatal accidents that occurred in the winter and summer months of the *Twilight Zones* and *Daylight Control* conditions for each of the seven age groups.

Figure 9 presents a summary of the fatal pedestrian and pedalcycle cases that occurred during the light (summer) and dim (winter) phases of the *Twilight Zones*. Figure 10 presents the same comparison for the *Daylight Control* condition; these control data should reveal effects of seasonal variables other than illumination. In both figures, dark bars represent the mean percentage of cases that occurred during winter months, when the *Twilight Zones* are darker than the midpoint of civil twilight (i.e., Nov., Dec. and Jan.), and the light bars present the mean percentage of cases that occurred during summer months, when the *Twilight Zones* are bright as the *Daylight Control* condition (i.e., May, June, and July). Data for female drivers are presented in the upper panels, and those for male drivers in the lower panels. The key feature to examine here is the relative height of the dark and light bars in each figure. These bars should be of equal height if there is no difference between the summer and winter months in the proportion of fatal pedestrian/ pedalcycle accidents during the relevant test condition. One can see in Figure 10 that pedestrian/ pedalcycle cases were more prevalent during summer months in the Daylight Control condition. The difference between summer and winter is greatest for the oldest female drivers. One should remember, however, that this category contains the smallest sample of all Age X Gender groups. The important point is that, for both genders at all ages, a greater proportion of fatal pedestrian/pedalcycle accidents occurred during the *Daylight Control* hours in the summer than in the winter. The opposite outcome is seen for the *Twilight Zones* in Figure 9. Here, a consistently higher proportion of cases occurred during the winter (dim) than during the summer (bright) months. Further, the *differences* between winter and summer months increases, as predicted, from the youngest through the fifth decade of age, after which the difference tends to diminish. This trend is clearer for male drivers, where the difference between winter and summer months increases through the 65-74 yr. group.

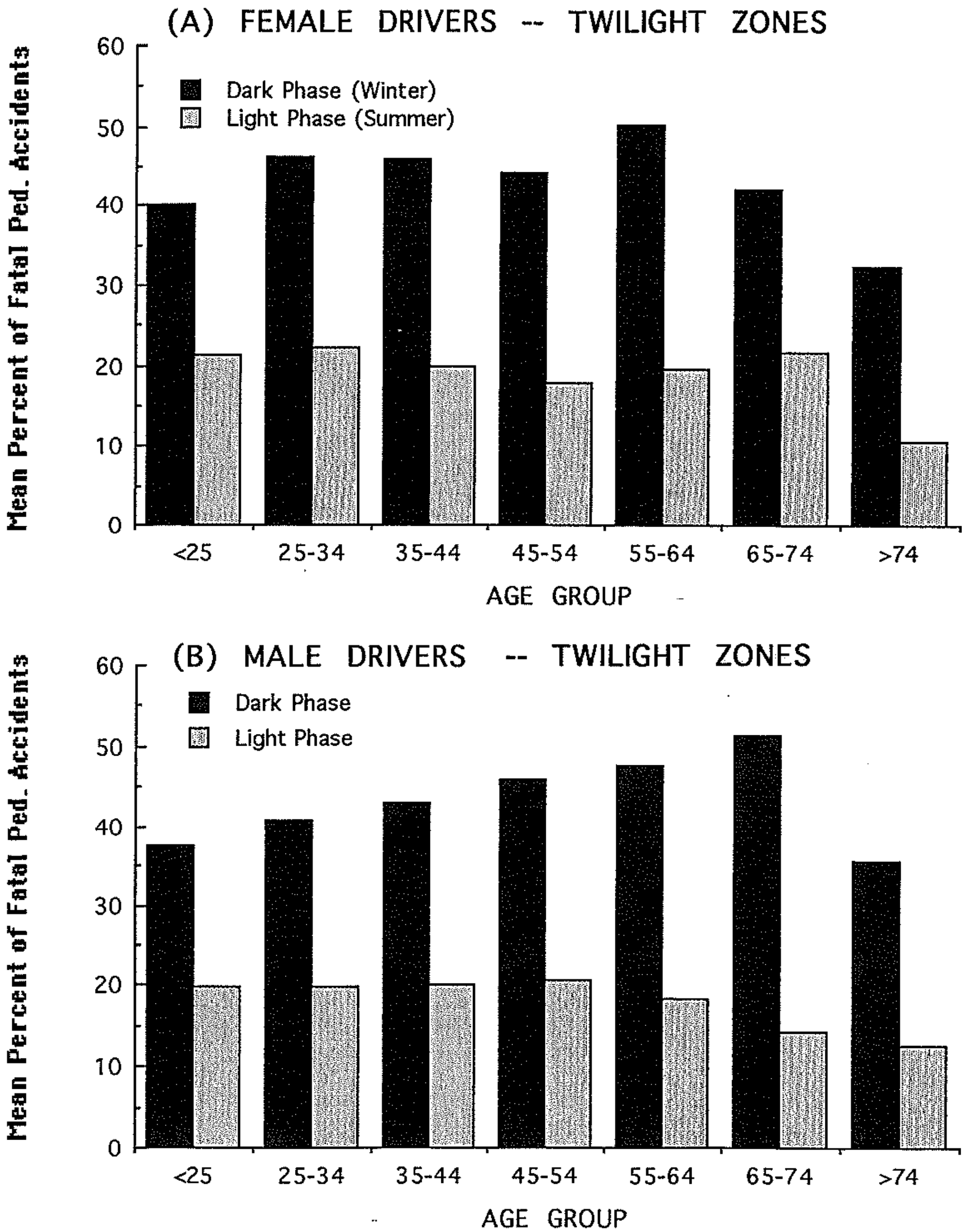

Figure 9. Mean percentage of fatal *Pedestrian/pedalcycle* accidents in the dim (winter) and bright (summer) months of the *Twilight Zones* for (A) female and (B) male drivers.

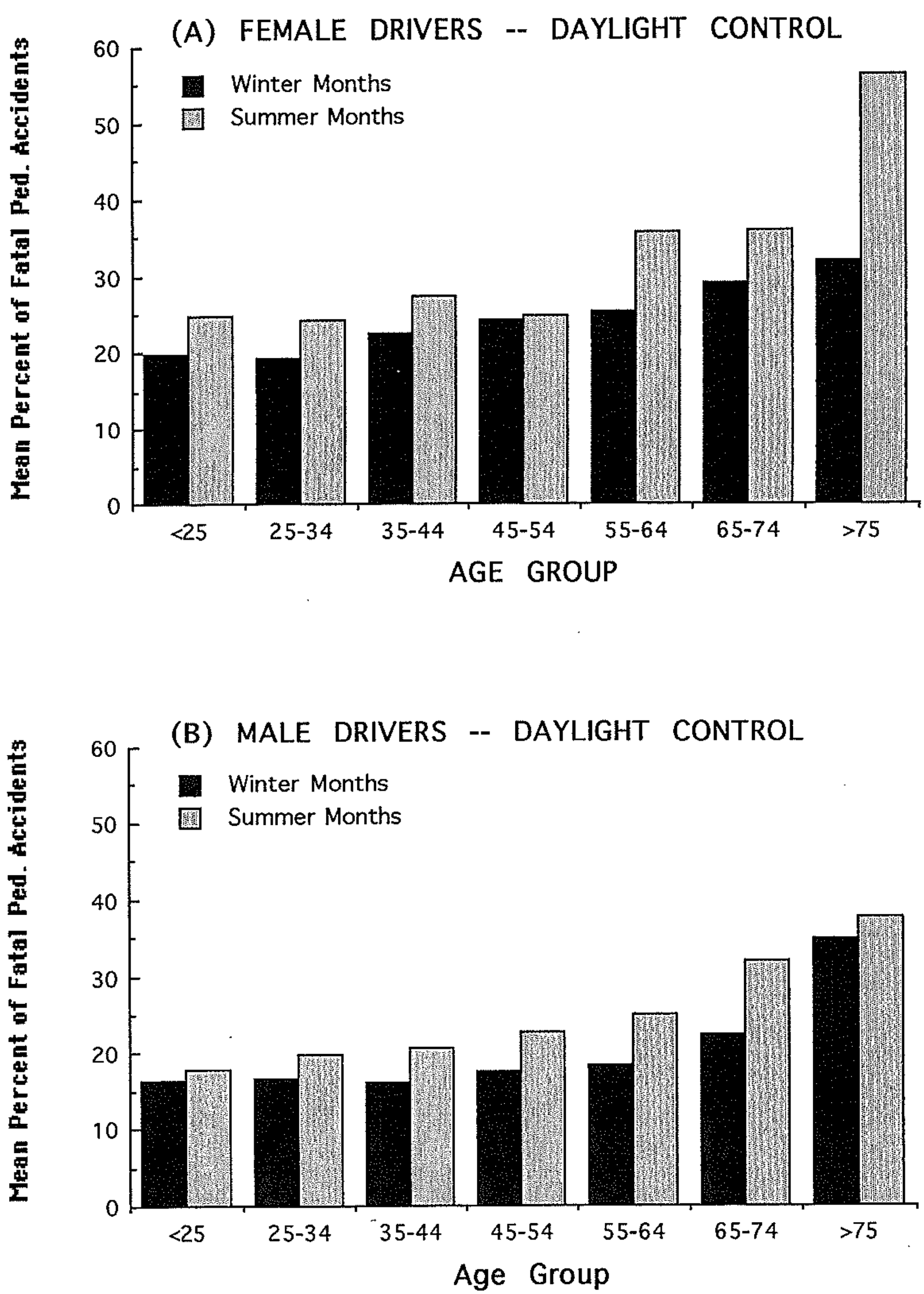

Figure 10. Mean percentage of fatal *Pedestrian/pedalcycle* accidents in the winter and summer months of the *Daylight Control* condition for (A) female and (B) male drivers.

To examine age-related trends more closely, the arithmetic differences illustrated in Figures 9 and 10 were replotted in Figure 11. Differences for the *Twilight Zones* are summarized on the left (panels A & B), while those for the *Daylight Control* are presented on the right (panels C & D). Three lines are seen in each panel: The horizontal solid line at zero represents the null prediction that there is no difference between winter and summer months in the proportion of cases during the given test period. Differences falling below that line indicate a greater proportion of cases in summer than winter, while differences above the line indicate a greater proportion of cases in winter than summer.

In the *Daylight Control* condition, data for *Other* (non-ped.) fatal accidents fall near the null prediction for both genders at all ages. This is important because is implies that there are no systematic differences between winter and summer in the proportion of this class accidents that occur during the *Daylight Control* period. On the other hand, data for the *Pedestrian/Pedalcycle* cases fall below the null prediction, indicating a greater proportion of cases during summer months in the *Daylight Control* period. Moreover, this higher representation of *Daylight* cases in the summer increases with age, especially for female drivers. This increase might reflect increased exposure of both pedestrians/ pedalcyclists and older drivers during the Daylight test periods in the summer as compared with the winter months. In any event, this trend stands in contrast to the results from the *Twilight Zones* condition.

Turning to the results for the Twilight Zones, one can observe a more striking difference in the pattern for *Other* and *Pedestrian/pedalcyclist* accidents. The proportion of fatal pedestrian/pedalcyclist cases is clearly higher in the winter (dim) than in the summer (bright) months of the *Twilight Zones*. Furthermore, this difference increases as a function of driver age until near the age of retirement, ranging from 18.8% in the youngest female group to 30.6% in the 55-64 year-old group of female drivers, and from 17.8% in the youngest male group to 37% in the 65-74 year-old group of male drivers. In the oldest groups, the overrepresentation of cases in the dim months receded toward that of younger drivers. The trends prior to retirement age are consistent with the hypothesized increase in the involvement of older drivers in fatal pedestrian and pedalcycle accidents during the dim phase of the *Twilight Zones*. It is interesting to note the similar, though much smaller, trend in data for *Other* (non-ped.) fatal accidents for the middle and older age groups. Male drivers beyond the age of 45 and females beyond the age of 55 showed 3.6% to 4.7% higher proportions of *Other* (non-ped.) fatal accidents in the winter (dim) as compared with the summer (light) months of the *Twilight Zones*.

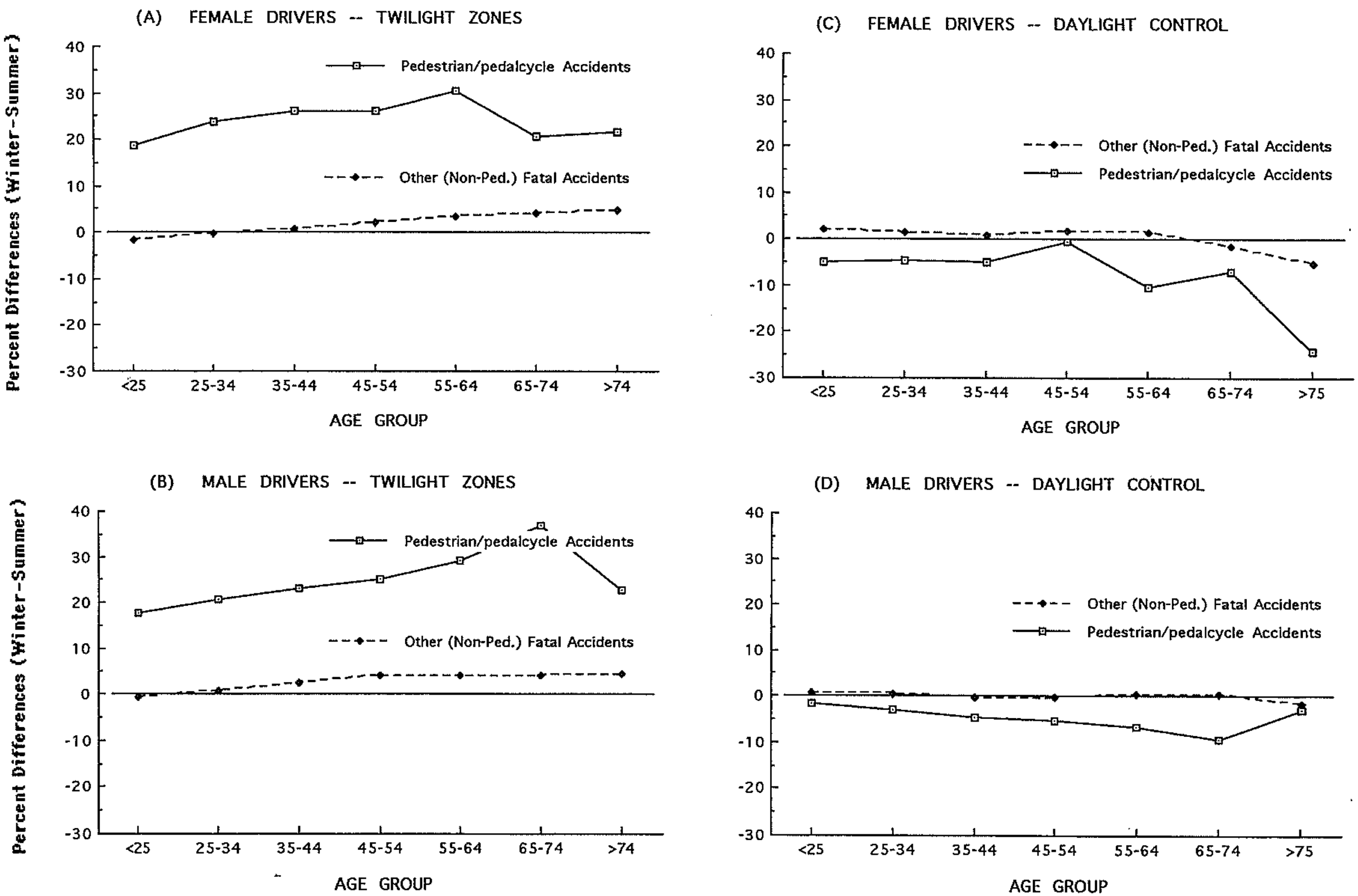

Figure 11. Difference of the percentages of fatal accidents occurring during the winter and summer months of the *Twilight Zones* (A & B) and the *Daylight Control* (C & D) conditions.

DISCUSSION

This study investigated the hypothesis that age-related changes in night vision may be associated with increased risk of involvement in fatal pedestrian/pedalcycle accidents during conditions of low illumination. It built upon an earlier quasi-experimental investigation that showed, without consideration of drivers' age, that this class of fatal collisions is disproportionately represented in low visibility conditions (Owens & Sivak, 1993). Of particular interest were variations during the morning and evening time-periods, called Twilight Zones, in which illumination from the sky varies systematically over the course of a year.

The previous investigation had revealed that the proportion of fatal *Pedestrian/pedalcycle* accidents occurring during the *Twilight Zones* varies on a monthly basis in close correlation with changes in natural illumination (Figs. 1 & 2). No such monthly variations were found for either (1) *Daylight Control* periods when pedestrians and pedalcyclists would be uniformly visible or (2) *Other* fatal accidents, in which visibility may be less problematic, for any test period (*Twilight Zones,* or *Daylight* and *Nighttime Controls*). The fact that variations of fatal pedestrian/pedalcycle accidents were selective to that class of accidents *and* were so closely correlated in time with changing natural illumination supported the inference that visibility, and not some other uncontrolled seasonal factor, is a primary contributor to these fatalities. This finding raised the possibility that normal age-related changes in vision, which impair night vision progressively over the adult life span, would produce predictable differences in the patterns of accident involvement, particularly for *Pedestrian/pedalcycle* accidents, in the *Twilight Zones* test condition. Specifically, we hypothesized that *differences between winter and summer months* in drivers' involvement in this class of accidents would increase as a function of age.

The main findings of the present study are summarized in Figure 11. As predicted, these data show that both female and male drivers exhibited increasing involvement in fatal *Pedestrian/pedalcycle* accidents during the dim, winter months as compared with the bright, summer months of the *Twilight Zones.* This key difference was found to increase gradually as a function of age, growing by roughly a factor of two from the youngest age groups through the age range typically associated with retirement. Interestingly, this increasing trend reversed in the oldest age groups returning to levels for younger groups. The apparent decline in the overrepresentation of cases in the dim months may result from decreasing exposure as the oldest drivers avoid low luminance conditions, or it may be related to other behavioral characteristics of the eldest drivers of the population. Although we cannot identify the reason for this decline, it is unlikely to reflect better vision on the part of the oldest drivers. Turning to data from the Daylight *Control* condition, it is important to note that there is no age-related increase in accident involvement during the winter months, but, on the contrary, there is a clear trend in the opposite direction, indicating a greater proportional involvement of older drivers in *Pedestrian/ pedalcycle* cases during the *summer* months.

Although the present experiment cannot specify the reason for the observed increase of Daylight *Pedestrian/pedalcycle* accidents in the summer for older drivers, one could hypothesize that it results from (1) increased exposure of pedestrians and pedalcyclists during the warmer summer months, and/or (2) a higher numbers of miles driven by older age groups during the summer. In any case, this opposite trend weighs against the possibility that age-related increases in *Pedestrian/pedalcycle* accidents during the winter months of the *Twilight Zones* are the result of an uncontrolled seasonal variable, such as weather or exposure. Rather, the results for the *Daylight Control* condition indicate that such uncontrolled seasonal factors tend to diminish involvement in pedestrian accidents in winter. These findings thus confirm the previous finding that, when natural illumination is low, fatal *Pedestrian/pedalcycle* accidents are more prevalent for drivers of all ages, and they support the hypothesis that the risks associated with poor visibility in low illumination increase with the age of the driver, at least until the age of retirement when drivers may be better able to avoid driving in low illumination.

It is interesting to note that a similar, though much less striking, pattern of results was found for *Other* (non-ped.) fatal accidents. In the *Daylight Control* condition, there was essentially no difference in winter-summer accident involvement prior to the age of 74. Thereafter, there was a slight tendency for greater accident involvement in summer than winter months. In the *Twilight Zones*, however, there was a small but consistent trend with increased age toward higher accident involvement in the winter months. This difference emerges gradually through middle-age, somewhat earlier for male than for female drivers, and it remains fairly stable at 3.6% to 4.7% beyond the age of 55. This finding suggests that age-related impairment of night vision contributes to *Other* classes of fatal accidents, as well as to the *Pedestrian /pedalcycle* category.

In summary, the findings illustrated in Figure 11 reinforce previous evidence that reduced visibility is an important contributor to fatal pedestrian/pedalcycle accidents. Furthermore, they indicate that aging drivers face an increasing risk of involvement in fatal *Pedestrian/pedalcycle* accidents and, to a lesser extent, also in *Other* classes of fatal accidents under conditions of low illumination. This gradual trend (i.e., from the youngest to the retirement-aged groups) is consistent with predictions based on age-related changes in basic visual processes. Unlike cognitive and motor processes (such as attention and response time), which show relatively little change until later in life, physiological changes in the visual system occur gradually over the life-span. Although few, if any, empirical studies of driving performance at night have studied multiple age groups across the adult life span, numerous experiments have documented the impairment of night vision for older as compared with younger drivers (e.g., Luoma, Schumann, & Traube, 1995; Owens, Sivak, Helmers, Sato, Battle, & Traube, 1992; Sivak, Olson, & Pastalan, 1981).

Physiological and psychophysical research has established that basic visual processes, which are critical for performance in low light, change progressively over much of the adult life span. Perhaps most important is the gradual reduction in maximum pupillary dilation, a process sometimes referred to as *senile miosis*, which begins in the early teens. While there are wide individual differences at all ages in maximum pupil diameter, the trend toward smaller pupils with age is universal (e.g., Loewenfeld, 1979; Weale, 1963). Because retinal illuminance is proportional to the *area* of the pupil, a reduction in pupil diameter from 8 mm to 4 mm, which is typical of changes from age 20 and 60 yrs. (e.g., Kornzweig, 1954, cited by Pitts, 1982), corresponds to a four-fold reduction of light at the retina. This change alone would produce a substantial decrement in visual acuity and contrast sensitivity at the mesopic luminances commonly encountered in twilight and nighttime driving (Owens, Francis, & Leibowitz, 1989). The density of the crystalline lens also increases over the life span, increasing both absorption and scatter of light that passes through the pupil. These optical changes, in conjunction with possible age-related changes in neural processing, progressively limit the range of dark adaptation, the ultimate sensitivity, and the ability of the eyes to recover from glare (e.g., Kline & Schieber, 1985; Olson, 1992; Owsley & Sloane, 1989). Recent studies of the perception of heading from optical flow (Warren, Blackwell, & Morris, 1989) and of steering performance in a simple driving simulator (Owens & Tyrrell, 1993) indicate that vehicle guidance in low light can also deteriorate with age. Thus, although systematic evidence for age-related changes in drivers' performance is sketchy, there is good reason on the grounds of physiological and psychophysical studies to expect gradual deterioration across the adult life span of vision in low light. It therefore seems plausible that the age-related increases in fatal accident involvement during the dim phase of the Twilight Zones is related, at least in part, to these normal and unavoidable changes in vision.

In addition to variations of accident patterns in the *Twilight Zones*, which were the focus of this study, the present findings revealed some more general effects of drivers' age and gender. As seen in Figure 3A, the total number of drivers involved in fatal accidents declines as a function of age, and throughout the life span there was a higher number of cases for male than for female drivers. These differences, well documented by earlier research, are due in part to covariations of the number of miles driven by various age/gender groups. The U.S. population has fewer old than young people, and a smaller portion of the older segment of the population is licensed to drive. Moreover, among licensed drivers, older individuals log fewer miles per year (Massie, Campbell, & Williams, 1995). Drivers over the age of 70 travel only 30-40% as many miles per year as those between the ages of 35-39 years (Evans, 1991; Massie et al., 1995). Similarly, female drivers generally drive fewer miles per year than male drivers. Reports of both Evans (1991) and Massie et al. (1995) show that males drive roughly twice as many miles per year as female drivers in middle-aged and older groups. Thus, even if female and male drivers were equally likely to encounter a fatal accident, males would be involved in substantially more fatal cases because of higher exposure.

Because of confounding differences in exposure, the role of age and gender cannot be inferred simply from the differences in the total numbers of accidents shown in Figure 3A. The important point for this investigation, however, was the fact that similar proportions of the total number of fatal accidents for both genders were included in the present test conditions. As seen in Figure 3B, the portion of cases was nearly identical for males and females in all but the oldest two age groups, where there was a somewhat reduced representation for female drivers. This similarity is an important safeguard against artifacts due to sampling error. That is, differences among the various age-gender groups (at least for groups younger than 65), which appeared through the quasi-experimental analyses, are not the result of disproportionate sampling of male and female drivers. This means that, although the present results do not depict the *rate* of accident involvement per miles driven, *they do present an accurate picture of the patterns of accident involvement* across three test conditions (*Daytime*, *Twilight Zones*, and *Nighttime*) for males and females across most of the adult life span.

An interesting interaction of the effects of age and gender can be seen in Figure 7. Three aspects of this figure merit close attention:

First, the proportion of fatal accidents occurring in the *Twilight Zones* is relatively stable for both genders until the age of 64, after which it declines. This reinforces the strength of inferences regarding the effects of age-related changes in vision that were based largely on data from the *Twilight Zones* condition. These important data are not distorted by sampling inequities for male and female drivers.

Second, for both genders, the proportion of fatal cases in the *Daylight Control* condition increased across the life span, while the proportion of cases in the *Nighttime Control* and, to a lesser extent, those in the *Twilight Zones* decreased. This shift in accident involvement from *Nighttime* to *Daylight* conditions may be related to corresponding age-related variations in overall exposure or, perhaps, other behavioral factors. The present experiment was not designed to isolate such factors. Nevertheless, the present findings do indicate that age-related changes of relative involvement in *Daylight* and *Nighttime* accidents are strikingly different for male and female drivers, which brings us to the third point.

The third notable feature of Figure 7 is a strong interaction between gender, age, and light condition. Close comparison of the upper and lower graphs shows that, throughout the life-span, male drivers exhibited higher relative involvement than female drivers in fatal accidents during the *Nighttime* as compared with the *Daylight Control* conditions. This interaction is most striking within the pre-retirement age range for which the data set comprises equal representation of both genders at all ages (Figure 3B). So it is not an artifact of disproportionate sampling, but rather a valid characteristic of 75% of the accidents recorded in the U.S. over a period of 14 years.

Past research on the roles of age and gender in serious accidents has shown that male drivers have consistently higher accident rates (per miles driven) than female drivers through early and middle adulthood (Evans, 1991; Massie, et al., 1995). The present findings suggest that this difference, especially in younger adults, may be attributable to a greater likelihood of male drivers to be involved in nighttime accidents. While specific causes for higher involvement of males in nighttime accidents cannot yet be specified, there is no reason to suppose that it is due to visual limitations unique to men. Rather, it seems more plausible that male drivers are more prone to engage in behaviors, such as alcohol consumption, that exacerbate the hazards of nighttime driving.

CONCLUSIONS

In summary, this investigation provides new experimental evidence that normal limitations of visibility are an important contributor to fatal road accidents. Analyses of the distribution of accidents during morning and evening periods in which natural illumination varies systematically has shown that road fatalities, particularly those involving pedestrians and pedalcycles, are much more prevalent in conditions of dim than of bright illumination. The major contribution of this study is new evidence that differential involvement in fatal accidents under dim and bright illumination increases progressively as a function of age. These age-related changes in accident involvement are probably a consequence of normal changes in basic ocular and neural processes that cause gradual deterioration of visual performance at low luminances. In addition to age-related changes in accident involvement associated with unavoidable losses of vision, the present results revealed a differential distribution of fatal accidents across Daylight and Nighttime conditions for male and female drivers. Throughout the life span, and especially in early adulthood, a much higher proportion of fatal accident cases for male drivers were found at night. This difference is not likely to be related to any gender-based difference in visibility, but rather it is probably associated with behavioral factors that contribute to nighttime road fatalities.

The present results confirm the hypothesis that difficulty seeing a low-contrast obstacle, such as a pedestrian or pedalcycle, in low illumination increases gradually with the age of the driver. This finding seems contrary to past assertions that age-related increases in the risk of serious accidents are due largely to declining abilities with age to survive serious injuries. That argument has been extended to claim that older drivers pose no increased risk to anyone but themselves. For example, in his influential review of the accident literature, Evans (1991, p. 37) asserts that "in no case did the 65 year-old driver pose a greater threat to pedestrians than did the 40 year-old driver." On the contrary, the present findings show that, under low luminance conditions, aging drivers really do pose greater hazards to other road users, particularly to pedestrians and pedalcyclists. One must bear in mind, however, that younger drivers, especially younger male drivers, appear to bring substantial age-related risks of their own to the night driving situation. These risks are not likely to be related to visual limitations and, viewed from the standpoint of public health and safety, they may well be accompanied by far greater costs than those associated with aging vision.

Progress toward ameliorating the tremendous costs of road accidents depends on clearer isolation and quantification of the role of specific contributing factors. Quasi-experimental analyses of extensive accident records, like the FARS database, appears to be a useful strategy for advancing this effort.

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